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Oil and Macroeconomy

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ABSTRACT

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Traditional literature on energy economics gives a central role to exogenous political events (supply shocks) or to global economic growth (aggregate demand shock) in modeling the oil market. However, more recent literature claims that the increased precautionary demand for oil triggered by increased uncertainty about a future oil supply shortfall is also driving the price of oil. The intuition for the precautionary demand motive is that since firms, using oil as an input in their production process, are concerned about the future oil prices, it is reasonable to think that in the case of uncertainty about future oil supply (such as a highly expected war in the Middle East), they will buy futures and/or forward contracts to guarantee a future price and quantity. We find that under baseline Taylor-type interest rate rule, real oil prices, inflation and output loss overshoot and go down below their steady state values at the next period if uncertainties are not realized. However, if the shock is realized, i.e. followed by an actual supply shock, the effect on inflation and output loss is high and persistent.

Second chapter analyzes the implications of storage market for the monetary policy formulation as a response to an oil price shock. Recent literature suggests that although high oil prices contributed to recessions, they never had a pivotal role in the creation of those economic downturns. A general consensus is that the decline

in output and employment was due to the rise in interest rates, resulting from the Fed's endogenous response to higher inflation induced by oil price shocks. However, traditional literature assumes that oil price shocks are exogenous to the U.S economy and ignores the storage market for crude oil. In this regard, a model with an endogenous (demand shock) or exogenous (supply shock) price shock may produce a totally different monetary policy proposal when a market for crude oil storage exists. The rationale behind this idea is that when goods prices are sticky in the economy, the monetary authority can affect the level of inventories through changes in real interest rates. Thus, lower interest rate rules, as proposed in the literature, will cause additional oil supply scarcity in the spot market. Therefore, an optimal monetary policy that maximizes the welfare in the economy should consider the adverse affect of low interest rates on the crude oil market.

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Chapter 1

Oil Price Shocks and Macroeconomy: The Role of Storage and Precautionary Demand

1.1 Introduction

The energy crisis of 1973-1974 coincided with one of the longest post-World War recessions. This gave rise to many studies on the effects of oil price increases on the economy. A large number of studies tried to establish theoretical links and document empirical evidence in support of the idea that oil prices were responsible for the recession, episodes of inflation, reduced productivity and declining economic growth. In fact, Figure 1.1 shows that 9 of the 10 recessions in the United States were preceded by a sharp rise in the price of oil.

However, closer examination of this fact reveals that the economy does not respond in the same way to oil price movements. To be precise, since the late 1990s, the global economy has experienced two oil shocks of sign and magnitude comparable to those of the 1970s, but, in contrast with the previous episodes, GDP growth and inflation have remained relatively stable in much of the industrialized world. In order to explain this difference, energy economics literature primarily takes two approaches. The first approach claims that the oil price shocks themselves were never important

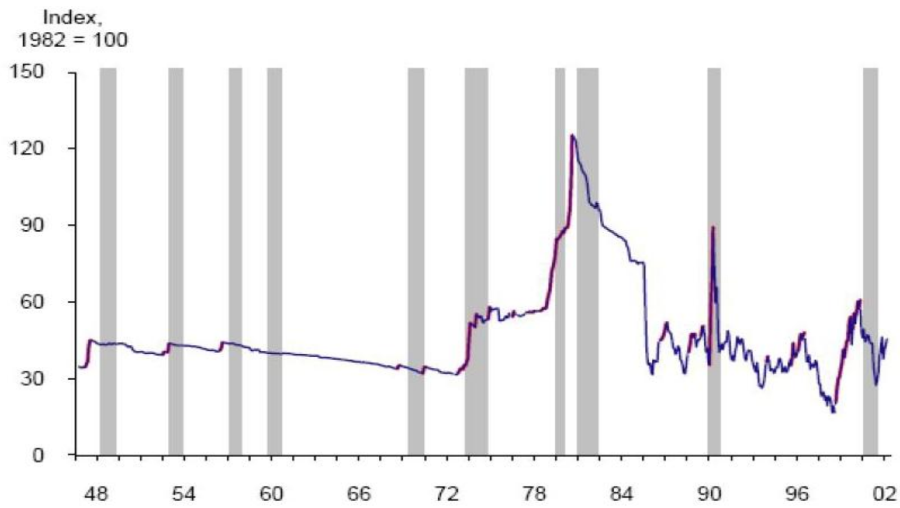

Figure 1.1 : Real oil prices and US recessions

factors behind those macroeconomic downfalls, their effects were rather exaggerated. In other words, according to some researchers (Bernanke et al. (1997), Wei (2003), Dhawan and Jeske (2006)) oil prices themselves are not the creators, but just the marginal contributors to those recessions. A second approach focuses on the nature of these shocks and challenges the notion that the major oil movements, at least, can be viewed as exogenous with respect to the U.S. economy (Barsky and Kilian (2001), Blanchard and Gali (2007a)).

This paper tries to explain the nature of oil price shocks and their effects on macroeconomic variables. Traditional literature on energy economics gives a central role to exogenous political events in modeling the oil prices. However, more recent studies (Barsky and Kilian (2001), Kilian (2009), Blanchard and Gali (2007a)) take a different stand and provide arguments in favor of reverse causality from macroeconomic variables to oil prices. Additionally, these papers draw attention to differences between oil prices shocks and their macroeconomic implications in the 1970s and 2000s. The main conclusion of these papers was that oil price shocks were caused by supply disruptions in the 70s and aggregate demand shocks in 2000-2008.

Kilian (2009), on the other hand, constructs a structural VAR model of the global crude oil market and concludes that oil price shocks have been driven mainly by a combination of global aggregate demand shocks and precautionary demand shocks, rather than simple oil disruptions caused by exogenous events in the Middle East. Kilian claims that while exogenous political events do affect oil prices, especially in the 1990s, it is less about the physical supply disruptions and more about the increased uncertainty about future oil supply shortfall which is driving the price of oil.

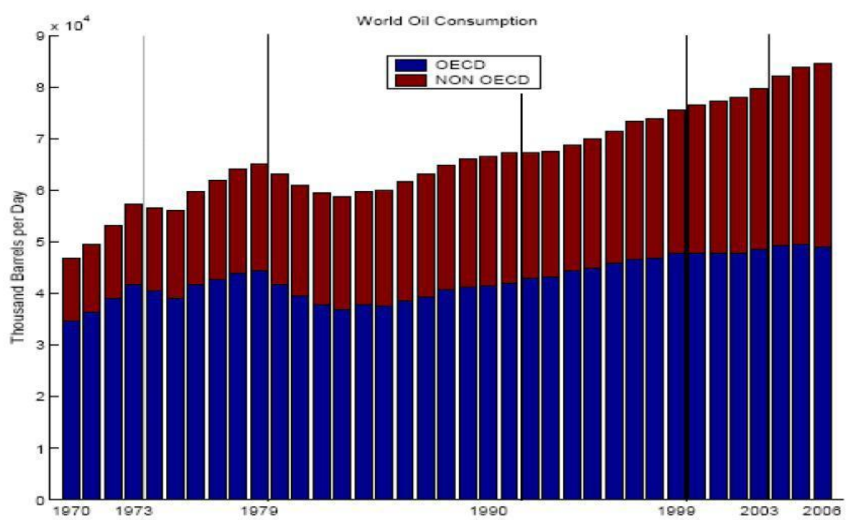

Figure 1.2 : World oil consumption (yearly average)

According to the energy economics literature (Kim and Loungani (1992), Hamilton and Herrera (2004)), oil price movements in 1973 and 1991 were caused by oil supply disruptions during exogenous events in the Middle East (OPEC embargo and Iraq-Kuwait war, respectively). However, as it is shown in Figure 1.2, yearly average world oil consumption was increasing in the aftermath of 1991, while decreasing during the 1973-75 OPEC embargo, which means that the supply cut argument is not valid for the 1991 oil price shock. Therefore, Kilian (2009) claims that the latter is caused by the precautionary demand motive of the firms using oil as an input for their production. This motive is usually triggered by a concern about a future oil supply disruption (for example, a highly expected war in the Middle East).

Based on this motivation, we built a theoretical model to quantify and examine the nature of oil price shocks caused by precautionary demand in the crude oil market. We constructed a standard DSGE model with the sticky-prices where firms can have access to an oil futures market. In this model, there is also the storage operators, who buy the oil in the spot market and hedge it by selling the oil futures in the futures market. Using this model, we simulated the effects of these demand shocks on the macroeconomic variables, such as GDP and inflation.

It is intuitive to think that in the case of an increased uncertainty about future oil supply, the firms using oil as an input will buy futures and/or forwards contracts to guarantee a future price and quantity. Moreover, higher demand in the futures market would encourage the storage operators to increase their inventories and, thus, create scarcity in the spot market for oil. That, in turn, will induce the spot price of oil to increase immediately. This modification was first introduced by Alquist and Kilian (2010) to derive the immediate effect of an uncertainty about the future oil supply shortfalls on the real spot price of oil. They model the oil supply of a foreign country as a stochastic mean-preserving process. When there is “news” today about the future availability of the oil, the variance of the oil endowment for tomorrow goes up permanently and creates an uncertainty shock. This setup allows us to separate the mean effect (supply shock) from the variance effect (uncertainty shock). Unlike Alquist and Kilian (2010), model also allows for temporary increases in the uncertainty. Similarly, news about the future availability of the oil supply creates an uncertainty in the market. However, if the concern of the agents are not realized (i.e. no supply shortfall), they will reasonably update their beliefs and become less and less concerned over time.

As another improvement on Alquist and Kilian (2010), we employ this extension in a standard cashless DSGE model with the sticky-prices (Woodford (2003)) to analyze the dynamics of macroeconomic variables when agitated by a future oil supply uncertainty. Since oil is used as an input in the production process, any surge in its price, caused by a future oil supply uncertainty or a current supply shortfall, will increase the production cost and lead to a ”supply side” disturbance in the economy.

Recently, we became aware of related work by Unalmis et al. (2012). They have independently studied the role of storage as a source of oil price shock and examined its macroeconomic effects. Their model is very similar to ours, however, they introduce speculative demand shock that ignores precautionary demand motives affected by second-order through the volatility in oil supply. Moreover, unlike Unalmis et al. (2012), our model allows for studying monetary policy implications of oil prices shocks in the presence of storage.

These findings also have important policy implications for thinking about the effects of oil price changes on the U.S. economy. Some recent literature suggests that although high oil prices contributed to recessions, they have never had a pivotal role in the creation of those economic downturns (Bernanke et al. (1997), Leduc and Sill (2004)). In this regard, tight monetary policy is often blamed for exaggerating the adverse effects of oil price shocks. As different oil price shocks cause different dynamics in income and inflation variation, one has to consider the nature of the shock before formulating a policy to cope with those adverse effects.

We find that under baseline Taylor-type interest rate rule, real oil price, inflation and output loss overshoot in the first period, but goes down below steady state at the next period if uncertainties are not realized. However, if the shock is realized, i.e. followed by an actual supply shock, the effect on inflation and output loss is high and persistent. In this case, the existence of storage increases the variability of macroeconomic variables and the real price of oil by transmitting future worries into todays decision making process.

The paper is organized as follows. Section 2 reviews the literature, Section 3 presents the model, Section 4 describes competitive equilibrium, market clearing conditions and aggregation. Section 5 discuss calibration and simulation results. Lastly, Section 6 concludes.

1.2 Literature Review

1.2.1 The Magnitude of the Oil Price Effect

Hamilton and Herrera (2004) and Hamilton (2005) point out that nine out of ten of the U.S. recessions since World War II and every recession since 1973 were preceded by a spike in oil prices. However, according to the Bureau of Economic Analysis and the Energy Information Administration, between 1970 and 2005, residential and commercial and industrial energy consumption was on average 4.8% and 4% of GDP, respectively. Based on this fact, change in oil prices can only explain a small fraction of the drop in GDP during a recession.

To solve this puzzle, Rotemberg and Woodford (1996) studied output impulse response functions and showed that under imperfect competition conditions the effect of oil price shock is stronger than the one observed under perfect competition conditions. They estimated that a 1 percent increase in energy prices lead declines in U.S. output of 0.25 percent and in U.S. real wages of 0.09 percent about five to six quarters later. Moreover, Finn (2000) shows that one can increase the response of an oil price shock even under perfect competition conditions if energy use is modeled as a function of capacity utilization. Finn argues that an increase in the price of energy works as an adverse technology shock to induce a contraction in the economic activity and the magnitude of the force exerted by energy price shock derives from the relationship between energy usage and capital services.

However, both papers are silent on the business cycle properties of the model in response to energy shocks. Precisely, they do not report the share of output fluctuations explained by energy price shocks and the other business cycle facts such as volatility of investment, consumption and co-movement of these variables. In fact, by incorporating energy use exclusively on the production side in DSGE models, Kim and Loungani (1992) claims that energy price fluctuations can only generate a small fraction of the output fluctuations observed in U.S. data. They even conclude that all previous recessions would have occurred even without energy shocks, since output is mainly driven by shocks to the total factor productivity.

To solve the controversy of low share in total expenditure and high share in output fluctuations, some studies claim that a jump in energy prices make a substantial fraction of the capital stock obsolete. Baily (1981) argues that as a result of high energy prices expected profits of machines in operation declines. The value of existing capital decreases as it is not technologically suited to new economic conditions. Besides, firms will not be willing to invest in new machinery, unless the high price lasts for a lengthy period. Therefore, this mechanism will lead to low levels of stock market prices. Although this link was realized in the literature, only Wei (2003) analyzes the causal link between energy price shock and stock marker crush in a partial-equilibrium setup. In a partial-equilibrium putty-clay model, where the real wage and interest rates are fixed exogenously, Wei finds that an 80-percent permanent increase in the real energy price leads to a 10-percent decline in the market value of previously installed machines. This impact is even smaller (only a 2-percent decline) in a general-equilibrium putty-clay model, which is an extreme case of rigidity in the adjustment of capital ex post. According to Wei (2003), the energy price increase causes real wages to decline by around 3.8 percent. The decline in real wages is large enough to offset most of the increase in cost coming from the capital side.

Lastly, some authors argue that stagflation of the 1970s was largely due to factors other than oil. Barsky and Kilian (2001) claim that stagflation may have been partly caused by exogenous changes in monetary policy, which coincided in time with the rise in oil prices. Bernanke et al. (1997) argue that much of the decline in output and employment was due to the rise in interest rates, resulting from the Feds endogenous response to the higher inflation induced by oil shocks.

1.2.2 What has changed lately?

Blanchard and Gali (2007b) define an oil shock as an episode where the overall increase in oil price has been higher than 50% and has lasted for more than one year. Following this criteria four oil shocks are identified for the period 1970 to 2005. Despite the fact that these oil shocks are similar in magnitude, they have been associated with very different macroeconomic performances. While the first two episodes (1973:2-1974:1 and 1978:4-1980:2) of oil price increase coincided with an increase in all inflation variables and a decrease in GDP growth and real wage, the last two episodes (1998:4-2000:4 and 2001:4-2005:3) coincide with a positive GDP growth rate, an increasing real wage and low inflation. In the light of these evidences, Blanchard and Gali (2007) try to explain the difference between various oil shocks assuming that the source of the change in oil price is always the same, i.e. an exogenous increase in oil price. They consider differences in monetary policy, in the degree of wage rigidity and the proportion of oil used in the production and show that a change in each of them can reduce the volatility of both price and quantity in response to the same oil shock.

However, Kilian (2009) and Balke et al. (2010) challenge the idea that oil price shocks were alike, i.e. exogenous. They underline the importance of identifying supply vs. demand shocks to oil prices. Balke et al. (2010) formulate that the oil price shocks of the 2000s occurred as a consequence of persistent increase in foreign productivity, while in the 1970s there was, simply, a reduction in oil supply. It is intuitive to expect different sources of oil price increase to convey different dynamics. Namely, an exogenous reduction in the supply of oil followed by high oil prices will boost marginal costs and there- fore deliver an increase in inflation. This scenario is consistent with the observed data of the 1970s, but cannot be applied to the 2000s.

An exogenous and persistent increase in productivity of a foreign country (such as China) in a simple two-country model leads to an increase in foreign GDP. Given the increased production, a persistent shock will induce a higher oil demand and therefore drive the oil price up. The home economy will still experience higher oil prices because of reduction in oil supply. However, there will be a reduction in the price of imported goods, as the foreign country is more productive now. As a result, CPI inflation in the home country may actually decrease, which in turn, generates an increase in real wages.

Lastly, the richer foreign country will buy more home goods, and therefore output in the home country will also increase. Apparently, this story tells us that the dynamics of oil price, inflation, real wages and GDP observed in the 2000s is consistent with an increase in oil demand driven by an increase in productivity in countries like China and India.

On the other hand, Kilian (2009) takes this analysis further and claims that there is even a third type of oil price shock. He provides a decomposition of real oil price into oil supply shock, shocks to the aggregate global demand for industrial commodities and demand shocks that are specific to the oil market (i.e. precautionary oil demand). Using this decomposition, he claims that, while the oil price increases in the 1970s were mainly due to precautionary demand increase, in the 2000s oil price shocks were caused by aggregate demand shocks.

1.3 The Model

This study extends the standard cashless Dynamic New Keynesian model as in Woodford (2003) by adding an oil market. There are two countries in this model: an oil-importer and an oil-exporter. The oil-importing country uses oil as an input in the production of intermediate goods. Oil is supplied by the oil-exporting country, who receives a random endowment in each period. The oil-exporting country uses oil income to purchase the end product of the oil-importing country.

1.3.1 The Oil-Importing Country

The oil-importing country consists of households, intermediate good producers, final good producers and storage operators. Oil is used in the production of intermediate goods, which are produced in a monopolistic market. Oil is sold both at the spot and the futures market.

The Final Good Sector

Final goods are produced in a perfectly competitive market by using a continuum of differentiated intermediate goods as inputs. The technology is defined by Dixit-Stiglitz aggregation formula,

$$Q_t = \left[\int_0^1 Q_t(i)^{\frac{\varepsilon-1}{\varepsilon}} \, di \right]^{\frac{\varepsilon}{\varepsilon-1}} \tag{1.1}$$

Profit-maximization and zero-profit conditions for these firms imply that the demand for intermediate good $Q_t(i)$ and the aggregate price level P_t are

$$Q_t(i) = \left[\frac{P_t(i)}{P_t} \right]^{-\varepsilon} Q_t \tag{1.2}$$

$$P_t = \left[\int_0^1 P_t(i)^{1-\varepsilon} \, di \right]^{\frac{1}{1-\varepsilon}} \tag{1.3}$$

The Intermediate Good Sector

There is a continuum of firms producing different varieties of intermediate goods under monopolistic competition. These firms have monopoly power over their output prices; however, they compete for inputs on competitive factor markets. Therefore, they act as price takers on factor markets, including the oil market. Besides, since these firms are very small, they take aggregate variables as given. The production function for an intermediate good producer type of i takes the following Cobb-Douglas form:

$$Q_t(i) = A_t K_t(i)^{\alpha_k} L_t(i)^{\alpha_l} O_t(i)^{\alpha_o} \tag{1.4}$$

Intermediate good producers are exposed to a common technological shock, A_t, which evolves exogenously according to $a_t = \eta_a a_{t-1} + \xi_{a,t}$, where $a_t \equiv \log A_t$ and $\xi_{a,t}$ is a white noise with zero mean and σ_a^2 variance.

Price Setting

Intermediate good producers operate in a monopolistically competitive market. We follow the literature on sticky-price models (Calvo (1983), Yun (1996)) and assume that although the firms have monopoly power over their own prices, they reset their prices only infrequently. At time t, only $1-\theta$ fraction of firms adjust their prices. The rest of the firms cannot adjust their prices and therefore set $P_t(i) = P_{t-1}(i)$.

A firm will maximize the expected discounted flow of future profits, if it gets a chance to change its price $P_t(i)$. The intermediate firm's problem in the goods market is as follows:

$$\max_{\tilde{P}_t(i)} E_t \, \Sigma_{k=0}^{\infty} (\theta)^k \Lambda_{t,t+k} [\tilde{P}_t(i) Q_{t+k}(i) - P_{t+k} mc_{t+k} Q_{t+k}(i)]$$

subject to downward-sloping demand function

$$Q_{t+k}(i) = \left(\frac{\tilde{P}_t(i)}{P_{t+k}}\right)^{-\varepsilon} Q_{t+k}$$

where $Q_{t+k}(i)$ is the demand for output produced by the firm i, and $\Lambda_{t,t+k}$ is the discount factor for the future nominal profits.

Futures Market:

Intermediate good producers also have access to the financial markets. In order to avoid uncertainty about future supply and about the price of oil, they buy futures contracts (X_t) supplied by storage operators*. As we discuss in next section, there is

*We state two different maximization problems for intermediate goods producers: goods market and futures market. However, one may suggest combining these problems. In other words, in addition to factor inputs, in each period firms can simultaneously choose the fraction of futures to be delivered, instead of settling by cash payment. In this case, firms will buy oil from the spot market if they need any in excess of the futures contracts provide them. However, we found out that no delivery in the futures market. Firms incur a profit (lost), if the price for futures fixed at t to be delivered at $t+1$ is less (higher) than the spot price of oil at $t+1$. The intermediate firm's problem in the futures market is:

$$\max_{X_t} \; E_0 \Sigma_{t=0}^{\infty} (\frac{1}{1+r_t})^t \Big[\frac{P^o_{t+1}}{P_{t+1}} - \frac{F_t}{P_{t+1}}\Big] X_t$$

Storage Operators

Storage operators buy oil at spot market to fill their inventories. we assume that the storage operators are risk-neutral, so all inventory is hedged by taking a long position in the oil futures market. This implies that at time t the storage operator promises to sell a certain amount of oil forF_t at time $t+1$. However, in the model there is no delivery, but only cash settlement. The operator sells all the inventory carried from previous period at the spot market ($P^o_t I_t$), settles the cash payments with the futures contract holders ($(F_{t-1} - P^o_t) I_t$), and chooses the amount of inventory for the next period (I_{t+1}). Besides, following the commodity pricing literature (Pindyck (2001)), we introduce the convenience yield, $g(I_t, \sigma^2)$, which refers to the flow of benefits to the inventory holders. These benefits arise from the fact that in the case of supply disruptions, the inventories can help to satisfy the demand in the market and smooth the production process. Therefore, the convenience yield is increasing in the level

the governing equations for this problem are the same as in maximizing two different problems.

of inventories ($g_1(I_t, \sigma_t^2) > 0)^\dagger$, but the marginal convenience yield of an additional inventory is decreasing ($g_{11}(I_t, \sigma_t^2) < 0$). Additionally, since higher uncertainty about the future oil supply (high σ_t^2) is more like to cause scarcity in the market, the marginal convenience yield is increasing ($g_{12}(I_t, \sigma_t^2) > 0$) in σ_t^2. Lastly, in order to ensure that the level of inventories is always positive, we assume that Inada condition $\lim_{I_t \to 0}\ g_1(I_t, \sigma_t^2) = \infty$ holds. The optimization problem for the storage operator is:

$$\max_{I_{t+1}} E_0 \Sigma_{t=0}^{\infty} (\frac{1}{1+r_t})^t \Big[\frac{F_{t-1}}{P_t} I_t - \frac{P_t^o}{P_t} I_{t+1} + g_t(I_{t+1}, \sigma_{t+1})\Big] \tag{1.5}$$

The first-order condition for this problem yields the no-arbitrage condition for the storage market:

$$E_t\Big[\frac{1}{1+r_t}\frac{F_t}{P_{t+1}}\Big] = \frac{P_t^o}{P_t} - g_1(I_{t+1}, \sigma_{t+1}) \tag{1.6}$$

Households

A representative household in the oil-importing country maximizes the following utility function:

$$E_0\ \Sigma_{t=0}^{\infty} \beta^t \Big[\log C_t - \frac{L_t^{1+\psi}}{1+\psi}\Big] \tag{1.7}$$

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†We denote g_i as the derivative of g with respect to i^{th} term, where g_{ij} implies cross-sectional derivative of g with respect to i and j.

Households earn labor income $w_tP_tL_t$, invest in risk-free bonds B_{t+1}, collect rent $r_t^kP_t\bar{K}_t$ from intermediate good producers and dividends ${\Pi_t}^f$ for their ownership in the firms.[‡]

$$P_tC_t + B_{t+1} = R_{t-1}B_t + w_tP_tL_t + P_tr_t^k\bar{K}_t + {\Pi_t}^f \tag{1.8}$$

Maximizing the utility function with respect to C_t, B_t and L_t will give us the following first-order conditions:

$$C_t{L_t}^{\psi} = w_t \tag{1.9}$$

$$\frac{1}{C_t} = \beta E_t\Big[\frac{1}{C_{t+1}}\frac{R_tP_t}{P_{t+1}}\Big] \tag{1.10}$$

Equation(9) and (10) jointly characterizes the household's decision rules for consumption, labor supply and bond holding.

1.3.2 Monetary Policy

We assume that the monetary authority in the oil-importing country follows a standard Taylor-type interest rate rule similar to the one estimated by Clarida et al.

[‡]Note that the aggregate capital stock is fixed at $\bar{K}_t$. Since the effects of oil price shocks on macro variables last 4-5 quarters at most, it is plausible to assume that capital is fixed.

(2000) to characterize the historical U.S. monetary policy. This policy sets the nominal interest rate for the risk-free bond to adjust output-inflation gap.

$$\hat{R}_t - \phi_R \hat{R}_{t-1} = (1 - \phi_R)\phi_\pi \pi_t + (1 - \phi_R)\phi_y \hat{y}_t \tag{1.11}$$

where $\hat{R}_t$ is the log deviation from steady-state nominal interest rate level ($\bar{R}$), $\pi_t = \log P_t/P_{t-1}$ and $\hat{y}_t$ is the log deviation of value-added from its steady state value. Since there is no cross-border borrowing, the value-added (GDP) in the oil-importing country will be

$$Y_t = C_t = Q_t - p_t^o \Omega_t \tag{1.12}$$

1.3.3 Oil-Exporting Country

The oil-exporting country is modeled as an endowment economy. In each period, it receives a random oil endowment Ω_t. Oil revenues are used to buy consumption goods produced in the oil-importing country. The oil-exporting country acts as a price-taker in spot market for oil and uses revenues to buy consumption goods from final goods producers.

$$P_t {C_t}^F = {P_t}^o \Omega_t \tag{1.13}$$

In order to disentangle “news” (variance) shock from the actual supply (mean) shock, I assume that the percentage deviation of the stochastic oil endowment from its steady state ($\hat{\omega}_t \equiv ln(\Omega_t) - ln(\bar{\Omega})$) has the following property:

$$\hat{\omega}_{t+1} = \rho\hat{\omega}_t + \ \xi_{t+1} \tag{1.14}$$

$$\xi_{t+1} = u_t \varepsilon_{t+1} \tag{1.15}$$

$$u_t = \lambda u_{t-1} + \sigma_u \eta_t \tag{1.16}$$

To be more concise, if there is no “news” , ($\eta_t = 0$), or in other words no uncertainty about the future availability of the oil supply, the oil endowment will be at steady-state level. On the other hand, if there is a “news shock” at time t ($\eta_t > 0$), the variance of the $\hat{\omega}_{t+1}$ will be positive. However, this does not necessarily imply that the supply will be less at $t + 1$, since there is a chance that the “news” will not be realized. In that case, agents will update their beliefs about the future (scale by $\lambda < 1$), and become less concerned.

1.4 Equilibrium, Market Clearing and Aggregation

1.4.1 Sticky-price Equilibrium

We assume a symmetric monopolistic competition equilibrium in which all intermediate good producing firms have identical behavior. In this equilibrium, at a given time some of the intermediate good producing firms cannot adjust their prices. However, those firms that optimize their profits, decide to charge the same price $\tilde{P}_t$. Therefore, the aggregate price index will be:

$$P_t = [(1-\theta)\tilde{P}_t^{1-\varepsilon} + \theta P_{t-1}^{1-\varepsilon}]^{\frac{1}{1-\varepsilon}} \tag{1.17}$$

If we denote $\tilde{p}_t = \frac{\tilde{P}_t}{P_t}$, then

$$\tilde{p}_t = \left[\frac{1-\theta\bar{\pi}_t^{\varepsilon-1}}{1-\theta}\right]^{\frac{1}{1-\varepsilon}} \tag{1.18}$$

1.4.2 Aggregation

Aggregate price dispersion has a distortionary effect on the aggregate output. If we denote aggregate price dispersion by $\Delta_t = \int_0^1 (\frac{P_t(i)}{P_t})^{-\varepsilon} di$, aggregate output will be the following:

$$Q_t = \frac{A_t K_t^{\alpha_k} L_t^{\alpha_l} O_t^{\alpha_o}}{\Delta_t} \tag{1.19}$$

where

$$L_t = \int_0^1 L_t(i)\ di \tag{1.20}$$

$$K_t = \int_0^1 K_t(i)\ di \tag{1.21}$$

$$O_t = \int_0^1 O_t(i)\ di \tag{1.22}$$

In the production factors market, monopolistic distortion caused by the intermediate good producing firms implies that labor, capital and oil are paid below their marginal product.

$$w_t L_t = \alpha_l mc_t Q_t \Delta_t \tag{1.23}$$

$$r_t^k K_t = \alpha_k mc_t Q_t \Delta_t \tag{1.24}$$

$$p_t^o O_t = \alpha_o mc_t Q_t \Delta_t \tag{1.25}$$

where real marginal cost $mc_t = \frac{p_t^{o\,\alpha_o} w_t{}^{\alpha_l} r_t^{k\,\alpha_k}}{A_t \alpha_o{}^{\alpha_o} \alpha_l{}^{\alpha_l} \alpha_k{}^{\alpha_k}}$ is common for all firms. Under flexible prices, monopoly distortion measured by mc_t is constant and less than unity. However, when prices are sticky, it responds to the real and nominal shocks in the economy. Therefore, an oil price shock affects the inputs market through the perturbation in mc_t.

Optimal price-setting decision $(\tilde{P}_t)$ by an intermediate good producing firm is governed by the following equations:

$$\frac{\tilde{P}_t}{P_t} \equiv \tilde{p}_t = \frac{E_t \Sigma_{k=0}^{\infty} (\beta\theta)^k \frac{Q_{t+k}}{C_{t+k}} X_{t,k}^{-\varepsilon} \frac{\varepsilon}{\varepsilon-1} mc_{t+k}}{E_t \Sigma_{k=0}^{\infty} (\beta\theta)^k \frac{Q_{t+k}}{C_{t+k}} X_{t,k}^{1-\varepsilon}} \equiv \frac{N_t}{D_t} \tag{1.26}$$

$$N_t = \frac{\varepsilon}{\varepsilon - 1} mc_t \frac{Q_t}{C_t} + \beta\theta E_t \bar{\pi}_{t+1}^{\varepsilon} N_{t+1} \tag{1.27}$$

$$D_t = \frac{Q_t}{C_t} + \beta\theta E_t \bar{\pi}_{t+1}^{\varepsilon} D_{t+1} \tag{1.28}$$

Decision rules for the intermediate firms and the storage operators in the financial mar- kets, which determine the equilibrium level of oil inventories and futures contracts, are characterized by the following equations:

$$E_t\ (p^o_{t+1}) = E_t\ (\frac{F_t}{P_{t+1}}) \tag{1.29}$$

$$E_t\Big[\frac{1}{1+r_t}\frac{F_t}{P_{t+1}}\Big] = p^o_t - g_1(I_{t+1}, \sigma^2_{t+1}) \tag{1.30}$$

1.4.3 Market Clearing

In equilibrium, net supply of risk-less bonds should be zero. Besides, since there is no capital accumulation, aggregate demand for capital is equal to the fixed supply.

$$B_t = 0 \tag{1.31}$$

$$K_t = 1 \tag{1.32}$$

In the oil market, oil supply is determined by the stochastic endowment (Ω_t) and the change in the level of inventories (ΔI_{t+1}). Therefore, the aggregate demand for oil, O_t, is equal to $\Omega_t - \Delta I_{t+1}$.

The oil-exporting country spends all the oil revenues on consumption good produced by the final good producers in the oil-importing country. Therefore, in the equilibrium, goods market clearing implies:

$$C^F_t = p^o_t O_t \tag{1.33}$$

$$C^F_t + C_t = Q_t \tag{1.34}$$

1.5 Calibration and Results

We follow the literature to calibrate the parameters for the utility and production functions. We set $\beta = 0.99$ corresponding to %4 annual steady-state real interest rate. Utility is logarithmic and the parameter $\psi = 1$ implying unit Frisch labor elasticity. There is no capital accumulation in the model, so the aggregate level of capital, $\bar{K}$, is set to 1. The labor, capital and oil elasticities of gross output are set to 0.63, 0.32 and 0.05, respectively. The elasticity of substitution among intermediate goods, ε, is set to 7.66 to match a steady-state price mark-up of %15 implying $\mu = 1.15$. Together with the oil elasticity of gross output, $\alpha_o = 0.05$, the price mark-up matches the average oil consumption share of U.S. GDP, which is 0.04. We assume that the intermediate firms can optimize their profits only once a year, so the Calvo price adjustment parameter, θ, is set to 0.75.

For the baseline analysis, we calibrate the monetary policy using the findings Orphanides (2001). Therefore, we set our baseline parameters to $\phi_R = 0.79$, $\phi_\pi = 1.8$ and $\phi_y = 0.27$. We will later simulate the model using alternative policies by changing the coefficients of the interest rate smoothing parameter and the coefficients of the contemporaneous inflation and the log-deviation of the output.

The persistence parameters for the technology (η), oil endowment (ρ) and the variance (λ) shocks are all set to 0.5. The calibration of these parameters do not have any significant qualitative effect on the results, as long as they are set positive numbers less than one.

Following Gorton et al. (2007), we set the marginal convenience yield parameter for the inventory at -130. The steady-state value of oil endowment and the inventory are chosen to be 0.5 and 0.05.

We solve the model by taking second-order Taylor expansion around deterministic steady-state with zero inflation in order to capture the variance effect and calculate impulse response functions for the specific shocks. To be more precise, the solution method follows the algorithm proposed by Benigno et al. (2010), which proposes a second-order approximation method for the solution of the dynamic stochastic models, where exogenous state variables display time-varying risk.

1.5.1 Precautionary Demand Shock

We model precautionary demand shock as a "news shock" to the variance of oil endowment. Once there is a shock to the σ_{t+1}, firms become worried about the future availability of the oil supply and demand more futures contracts to offset that uncertainty. On the other hand, the storage operators increase their inventories to sell more futures contracts. In order to show formally how the uncertainty about future oil supply may increase the real spot price oil, we solve the maximization problem for the storage operators and the intermediate good producing firms, and aggregate production to get the following equation:

$$\underbrace{mc_t Q'(\Omega_t - \Delta I_{t+1})}_{p_{o,t}} = E_t[\frac{1}{1+r_t}\underbrace{mc_{t+1}Q'(\Omega_{t+1} - \Delta I_{t+2})}_{p_{o,t+1}}] + g_1(I_{t+1}, \sigma_{t+1}) \tag{1.35}$$

When there is a "news shock" at time t, not followed by any change in the mean at time $t+1$ (i.e. no realization), right-hand side of the equation goes up, since $g_{12} > 0$ and $E[Q'(\cdot)]$ is disturbed upward by Jensen inequality as $Q'(\cdot)$ is convex. In order to offset that wedge, the level of inventory holdings decided to hold at time t to be used at time $t+1$, I_{t+1}, will increase to raise the left-hand side through ΔI_{t+1} and lower the right-hand side of the equation through ΔI_{t+2} and $g_1(\cdot)$. Meantime, we will observe a spike in the real spot price of oil, $p_{o,t}$, since it is equal to $mc_t Q'(\Omega_t - \Delta I_{t+1})$.

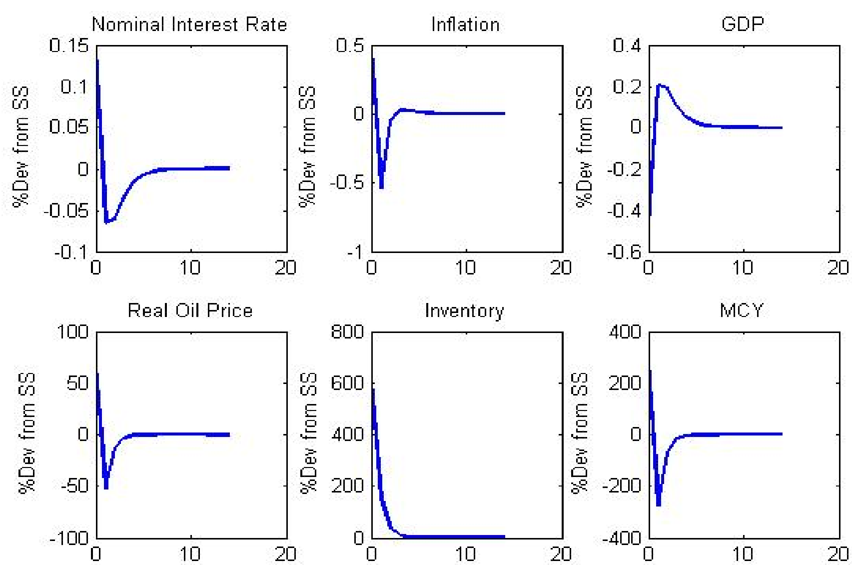

Figure 1.3 : Shock to the variance ($\eta_t = 1$), no realization ($\varepsilon_t = 0$ for all t)

We simulate the model with the benchmark Taylor-rule estimated by Orphanides (2001) using real-time data for 1979:1995. Figure 1.3 shows the dynamics of inflation, percentage deviation of GDP, inventory, real oil price and interest rates from their steady state values responding one standard deviation in σ_{t+1}.

In accordance with the model, changes in inflation, inventories and oil price are positive and output is negative at the first period. However, they turn to negative (positive for output) during the second period, since oil supply shortfall does not occur. The level of oil inventories do not return to the steady-state level immediately, since there is still concern, although less, about $t+2$. Besides, the amount of oil in the economy, $\Omega - \Delta I_{t+2}$ is higher than its steady state value, so the spot price of oil and inflation are below and output above their steady-state values. Oil abundance lasts as long as the uncertainty is not vanished and oil supply shortfall does not occur. It is also worth mention that the dynamics of marginal convenience yield (denoted by MCY in Figure 1.3) shows how markets can operate in contango. In other words, futures price can go above expected future spot price because of high uncertainty in supply and decline back overtime to converge to the future spot price. High marginal convenience yield realized at time t offsets the loss of storage operators incurred at $t+1$ due to lower future spot price of oil.

The difference can be seen in Figure 1.4, where an uncertainty shock at time t is followed by a supply shock at time $t+1$. Since there is no more oil abundance in the economy during the later periods, inflation and oil price stay above and output below their steady-state values.

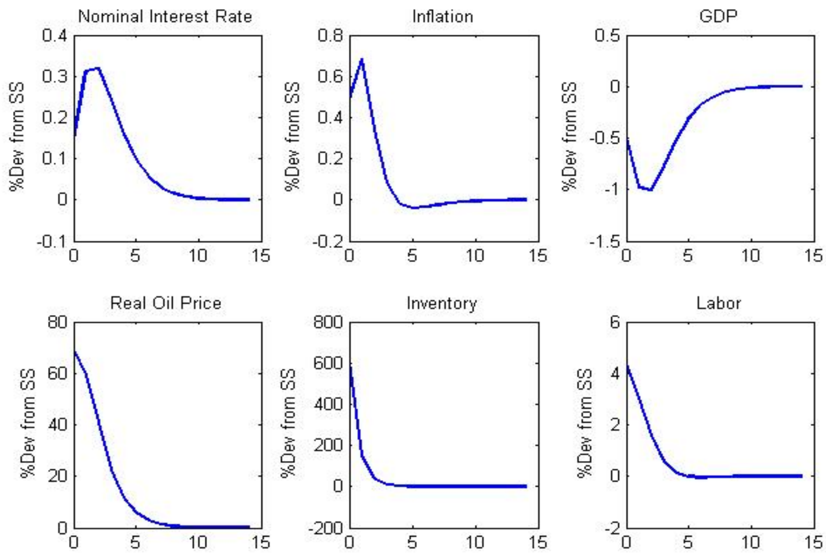

Figure 1.4 : Shock to the variance ($\eta_t = 1$) followed by a shock to the mean ($\varepsilon_{t+1} = -1$)

1.6 Conclusion

In this study we model and quantify the effect of uncertainty about future availability of oil supply on the macroeconomic variables. Our setup allows us to separate mean effect (supply shock) from variance shock (uncertainty effect). Under baseline Taylor-type interest rate rule, real oil price,inflation and output loss overshoot during the first period, but go down below steady state during the next period if uncertainties are not realized. However, if this shock is realized, i.e. followed by an actual supply shock, the effect on inflation and output loss is high and persistent.

Chapter 2

Oil Price Shocks and Monetary Policy: The Role of Storage

2.1 Introduction

Some recent literature suggests that although high oil prices contributed to recessions, they have never had a pivotal role in the creation of those economic downturns. A general consensus is that the decline in output and employment was due to the rise in interest rates, resulting from the Fed's endogenous response to the higher inflation induced by oil price shocks, as shown in Figure 2.1.

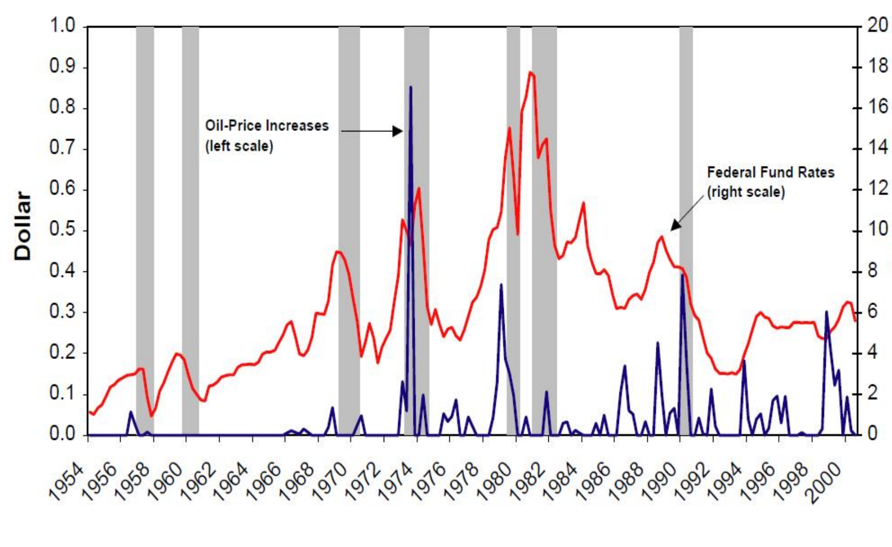

Figure 2.1 : Real oil prices, US Recessions and Federal Funds Rate

In this vein, Bernanke et al. (1997) argued that much of the decline in output and employment was due to the rise in interest rates, resulting from the Feds endogenous response to the higher inflation induced by oil price shocks. Leduc and Sill (2004) and Carsltrom and Fuerst (2006) calibrated a stochastic general equilibrium model in which oil was used as an input in production. They run counter-factual experiments to explore the role of alternative monetary policies in exacerbating or easing the response of economy to oil price shocks. They concluded that the Fed could pursue a different monetary policy and dampen the recessionary effects of those shocks. Barsky and Kilian (2001) claimed that stagflation may have been partly caused by exogenous changes in monetary policy, which coincided in time with the rise in oil prices.

However, all these papers assume that oil price shocks are exogenous to the U.S economy. In this regard, a model with an endogenous (demand shock) or exogenous (supply shock) price shock may produce a totally different monetary policy proposal when there exists a market for crude oil storage. Frankel (2008) shows the high correlation between commodity prices and the real interest rates. The rationale behind this idea is that when good prices are sticky in the economy, the monetary authority can affect the level of inventory through the changes in real interest rates. Although the monetary authority can only set nominal interest rates, when good prices are sticky, in the short-run these changes in the nominal interest rates will also affect real interest rates. Thus, lower real interest rates, as proposed in the literature to ease the adverse effects of oil price shocks, decrease the cost of inventories, so they decrease the incentive to extract today and/or increase storage operators desire to carry more inventory. This, in turn, decreases the quantity of oil supplied in the market and increases the spot price of oil. Therefore, an optimal monetary policy that maximizes the welfare in the economy should consider the adverse affect of low interest rates on the crude oil market. Based on these facts, I build a standard cashless DSGE model with sticky prices to study the monetary policy implications of oil price shocks. Following the commodity pricing and storage literature, I include both spot and storage market for oil, where storage operators store the oil and sell in the futures market. I analyze the role of alternative monetary policies in amplifying or dampening the economys response to oil price shocks and calculate the optimal welfare-maximizing monetary policy and optimal operational simple rule that mimics the optimal plan.

We run counter-factual experiments to explore whether the recessionary consequences of oil price shocks can be eliminated or dampened by another rule. In contrast with the literature, which ignores storage and financial markets, we find that neither the interest-rate peg (Bernanke, Gertler and Watson (1997)) nor the low-interest rate rules (Leduc and Sill (2004)) clearly dominates other interest-rate rules. Instead, optimal monetary policy dictates the higher nominal interest rates as a response to an oil price shock, regardless of the source. However, the source of the shock plays an important role in determining the magnitude and variation of the nominal interest rate.

2.2 Literature Review

According to the Bureau of Economic Analysis and the Energy Information Administration, between 1970 and 2005, residential and commercial and industrial energy consumption was on average 4.8% and 4% of GDP, respectively. Based on this fact, one may reasonably conclude that any change in oil prices can only cause a small drop in GDP, not necessarily lead to a recession. However, Hamilton (2005) points out that nine out of ten of the U.S. recessions since World War II and every recession since 1973 were preceded by a spike in oil prices. This led researchers to look for a transmission mechanism that possibly exaggerated the adverse effects of oil price shocks. Among several explanations including real wage rigidity and capital-energy complementarity; tight monetary policy is the one most likely to blame for amplifying macroeconomic downfalls in the advent of oil price increases.

Early empirical work by Bernanke et al. (1997), claimed that recessionary effects of the oil price shocks could actually be eliminated, if the Fed followed a neutral policy such as interest-rate peg. However, the claims were criticized in the literature, as the Lucas critique advocates running alternative policy experiments with reduced form estimates may not produce correct results. Leduc and Sill (2004) was the first paper to study the contribution of monetary policy using a calibrated general equilibrium model. According to Leduc and Sill (2004), fixed nominal interest rate rule is not capable of fully eliminating the adverse effects of oil price shocks. Among the sample of reasonable monetary policy rules, their results favor the one targeting the general price level of the economy (weighted average of core inflation and the percentage change in oil price).

Kilian and Lewis (2011) claim there is no evidence that the monetary authority was responding to oil price shocks before 1987, although the changes in federal funds rate and oil prices coincided during the spikes in the latter oil price shocks. However, during the post-1987 period, they also found that the monetary authority was using federal funds rate to cope with inflation triggered by an oil price shock, rather than responding to that shock directly.

Wrinkler (2009) calculated optimal monetary policy response to an anticipated and an unanticipated oil price shock and concluded that the optimal policy dictates a larger drop in output compared with the historical Taylor-rule. He also claims that divine coincidence*, controlling both the inflation and output gap at the same time, is not practical anymore, as optimal policy is not capable of stabilizing both simultaneously.

Lastly, Bodenstein et al. (2012), a multi-country DSGE model, estimates the optimal monetary response (welfare-maximizing) to the endogenous and the exogenous oil price shocks. Their main finding is that no oil price shock requires the same monetary response. Therefore, the monetary authority should disentangle the source of the shock before formulating any response. Lastly, they claim that optimal monetary policy calls for a higher weight on output gap and less on inflation compared to the

*See Blanchard and Gali (2007b) for more details on 'divine coincidence'.

historical monetary policy rule estimated from the data. A similar conclusion was drawn by Nakov and Pescatori (2010), who modeled an oil market consisting of a dominant producer that sets the monopoly price and many fringe competitors. They also claim it is not welfare-maximizing to respond directly to the oil price fluctuations, but rather to respond to inflation and output gap associated with those fluctuations.

Bodenstein et al. (2012) is the closest study to ours, as it focuses on the source of the shocks while formulating the optimal policy response. This paper, however, also takes into account the storage market for oil in addition to a standard spot market and builds a model where agents can buy oil futures to offset any future uncertainty about the price and quantity of oil. First, our setup allows analyzing the macroeconomic dynamics and monetary policy implications for the precautionary demand shocks triggered by the uncertainty about future availability of oil. Second, it takes into account additional transmission channels for the monetary policy through the storage market. In other words, since the cost of storage directly depends on the real interest rates, monetary authority can influence it by manipulating nominal interest rate when prices are sticky.

2.3 The Model

This study extends the standard cashless Dynamic New Keynesian model as in Woodford (2003) by adding an oil market. The are two countries in this model: an oil-importer and an oil-exporter. The oil-importing country uses oil as an input in the production of intermediate goods. Oil is supplied by the oil-exporting country, who receives a random endowment in each period. The oil-exporting country uses oil income to purchase the final good produced by the final good producers in the oil-importing country.

2.3.1 The Oil-Importing Country

The oil-importing country consists of households, intermediate good producers, final good producers and storage operators. Oil is used in the production of intermediate goods, which are produced in a monopolistically competitive market. Oil is sold both at the spot and the futures market.

The Final Good Sector

Final good is produced under perfect competition using continuum of differentiated intermediate goods as inputs. The technology is defined by Dixit-Stiglitz aggregation formula,

$$Q_t = \Big[\int_0^1 Q_t(i)^{\frac{\varepsilon-1}{\varepsilon}}\ di\Big]^{\frac{\varepsilon}{\varepsilon-1}} \tag{2.1}$$

Profit-maximization and zero-profit condition for these firms implies that the demand for intermediate good $Q_t(i)$ and the aggregate price level P_t are

$$Q_t(i) = \Big[\frac{P_t(i)}{P_t}\Big]^{-\varepsilon} Q_t \tag{2.2}$$

$$P_t = \left[\int_0^1 P_t(i)^{1-\varepsilon} \, di \right]^{\frac{1}{1-\varepsilon}} \tag{2.3}$$

The Intermediate Good Sector

There is a continuum of firms producing different varieties of intermediate goods under monopolistic competition. These firms have monopoly power over their output prices, however, they compete for inputs on competitive factor markets. Therefore, they act as price takers on factor markets, including the oil market. Besides, since these firms are very small, they take aggregate variables as given. The production function for an intermediate good producer type of i takes the following Cobb-Douglas form:

$$Q_t(i) = A_t K_t(i)^{\alpha_k} L_t(i)^{\alpha_l} O_t(i)^{\alpha_o} \tag{2.4}$$

Intermediate good producers are exposed to a common technological shock, A_t, which evolves exogenously according to $a_t = \eta_a a_{t-1} + \xi_{a,t}$, where $a_t \equiv \log A_t$ and $\xi_{a,t}$ is a white noise with zero mean and σ_a^2 variance.

Price Setting

Intermediate good producers operate in a monopolistically competitive market. I follow the literature on sticky-price models (Calvo (1983), Yun (1996)) and assume that although the firms have monopoly power over their own prices, they reset their prices only infrequently. At time t, only $1-\theta$ fraction of firms adjust their prices. The rest of the firms cannot adjust their prices and therefore set $P_t(i) = P_{t-1}(i)$.

A firm will maximize the expected discounted flow of future profits, if it gets a chance to change its price $P_t(i)$. The intermediate firm's problem in the goods market is as follows:

$$\max_{\tilde{P}_t(i)} E_t \, \Sigma_{k=0}^{\infty} (\theta)^k \Lambda_{t,t+k} [\tilde{P}_t(i) Q_{t+k}(i) - P_{t+k} mc_{t+k} Q_{t+k}(i)]$$

subject to downward-sloping demand function

$$Q_{t+k}(i) = \left(\frac{\tilde{P}_t(i)}{P_{t+k}}\right)^{-\varepsilon} Q_{t+k}$$

where $Q_{t+k}(i)$ is the demand for output produced by the firm i, and $\Lambda_{t,t+k}$ is the discount factor for the future nominal profits.

Futures Market:

Intermediate good producers also have an access to the financial markets. In order to avoid uncertainty about future supply and about the price of oil, they buy futures contracts (X_t) supplied by storage operators[†]. As I discuss in next section, there is

[†]I state two different maximization problem for intermediate good producers: goods market and futures market. However, one may suggest to combine these problems. In other words, in addition to factor inputs, in each period firms can simultaneously choose the fraction of futures to be delivered, instead of settled by cash payment. In this case, firms will buy oil from the spot market if they need any in excess of the futures contracts provide them. However, I found out that the governing

no delivery in the futures market. Firms incur a profit (lost), if the price for futures fixed at t to be delivered at $t+1$ is less (higher) than the spot price of oil at $t+1$. The intermediate firm's problem in the futures market is:

$$\max_{X_t} \ E_0 \Sigma_{t=0}^{\infty} (\frac{1}{1+r_t})^t \left[\frac{P^o_{t+1}}{P_{t+1}} - \frac{F_t}{P_{t+1}}\right] X_t$$

Storage Operators

Storage operators buy oil at spot market to fill their inventories. I assume that the storage operators are risk-neutral, so all inventory is hedged by taking a long position in the oil futures market. This implies that at time t the storage operator promises to sell a certain amount of oil for F_t at time $t+1$. However, in the model there is no delivery, but only cash settlement. The operator sells all the inventory carried from previous period at the spot market ($P^o_t I_t$), settles the cash payments with the futures contract holders ($(F_{t-1} - P^o_t) I_t$), and chooses the amount of inventory for the next period (I_{t+1}). Besides, following the commodity pricing literature (Pindyck (2001), we introduce the convenience yield, $g(I_t, \sigma^2)$, which refers to the flow of benefits to the inventory holders. These benefits arise from the fact that in the case of supply disruptions, the inventories can help to satisfy the demand in the market and smooth the production process. Therefore, the convenience yield is increasing in the level

equations for this problem are the same as in maximizing two different problems.

of inventories ($g_1(I_t, \sigma_t^2) > 0$)[‡], but the marginal convenience yield of an additional inventory is decreasing ($g_{11}(I_t, \sigma_t^2) < 0$). Additionally, since higher uncertainty about the future oil supply (high σ_t^2) is more like to cause scarcity in the market, the marginal convenience yield is increasing ($g_{12}(I_t, \sigma_t^2) > 0$) in σ_t^2. Lastly, in order to ensure that the level of inventories is always positive, we assume that Inada condition $\lim_{I_t \to 0}\ g_1(I_t, \sigma_t^2) = \infty$ holds. The optimization problem for the storage operator is:

$$\max_{I_{t+1}} E_0 \Sigma_{t=0}^{\infty} (\frac{1}{1+r_t})^t \Big[\frac{F_{t-1}}{P_t} I_t - \frac{P_t^o}{P_t} I_{t+1} + g_t(I_{t+1}, \sigma_{t+1})\Big] \tag{2.5}$$

The first-order condition for this problem yields the no-arbitrage condition for the storage market:

$$E_t\Big[\frac{1}{1+r_t}\frac{F_t}{P_{t+1}}\Big] = \frac{P_t^o}{P_t} - g_1(I_{t+1}, \sigma_{t+1}) \tag{2.6}$$

Households

A representative household in the oil-importing country maximizes the following utility function:

$$E_0\ \Sigma_{t=0}^{\infty} \beta^t \Big[\log C_t - \frac{L_t^{1+\psi}}{1+\psi}\Big] \tag{2.7}$$

[‡]We denote g_i as the derivative of g with respect to i^{th} term, where g_{ij} implies cross-sectional derivative of g with respect to i and j.

Households earn labor income $w_t P_t L_t$, invest in risk-free bonds B_{t+1}, collect rent $r_t^k P_t \bar{K}_t$ from intermediate good producers and dividends ${\Pi_t}^f$ for their ownership in the firms.[§]

$$P_t C_t + B_{t+1} = R_{t-1} B_t + w_t P_t L_t + P_t r_t^k \bar{K}_t + {\Pi_t}^f \tag{2.8}$$

Maximizing the utility function with respect to C_t, B_t and L_t will give us the following first-order conditions:

$$C_t {L_t}^{\psi} = w_t \tag{2.9}$$

$$\frac{1}{C_t} = \beta E_t \Big[\frac{1}{C_{t+1}} \frac{R_t P_t}{P_{t+1}} \Big] \tag{2.10}$$

Equation(9) and (10) jointly characterizes the household's decision rules for consumption, labor supply and bond holding.

2.3.2 Monetary Policy

We assume that the monetary authority in the oil-importing country follows a standard Taylor-type interest rate rule is similar to the one estimated by Clarida et al.

[§]Note that the aggregate capital stock is fixed at $\bar{K}_t$. Since the effects of oil price shocks on macro variables last 4-5 quarters at most, it is plausible to assume that capital is fixed.

(2000) to characterize the historical U.S. monetary policy. This policy sets the nominal interest rate for the risk-free bond to adjust output-inflation gap.

$$\hat{R}_t - \phi_R \hat{R}_{t-1} = (1-\phi_R)\phi_\pi \pi_t + (1-\phi_R)\phi_y \hat{y}_t \tag{2.11}$$

where $\hat{R}_t$ is the log deviation from steady-state nominal interest rate level ($\bar{R}$), $\pi_t = \log P_t/P_{t-1}$ and $\hat{y}_t$ is the log deviation of value-added from its steady state value. Since there is no cross-border borrowing, the value-added (GDP) in the oil-importing country will be

$$Y_t = C_t = Q_t - p_t^o \Omega_t \tag{2.12}$$

2.3.3 Oil-Exporting Country

The oil-exporting country is modelled as an endowment economy and acts as a price-taker in the spot market for oil. In each period, it receives a random oil endowment Ω_t. Oil revenues are used to buy consumption good produced in the oil-importing country.

In each period, the oil-exporting country acts as a price-taker in spot market for oil and uses revenues to buy consumption goods from final good procuders.

$$P_t {C_t}^F = {P_t}^o \Omega_t \tag{2.13}$$

In order to disentangle "news shock" from the mean shock, I assume that the percentage deviation of the stochastic oil endowment from its steady state ($\hat{\omega}_t \equiv ln(\Omega_t) - ln(\bar{\Omega})$) has the following property:

$$\hat{\omega}_{t+1} = \rho\hat{\omega}_t + \ \xi_{t+1} \tag{2.14}$$

$$\xi_{t+1} = u_t \varepsilon_{t+1} \tag{2.15}$$

$$u_t = \lambda u_{t-1} + \sigma_u \eta_t \tag{2.16}$$

To be more concise, if there is no "news", ($\eta_t = 0$), or in other words no uncertainty about the future availability of the oil supply, the oil endowment will be at steady-state level. On the other hand, if there is a "news shock" at time t ($\eta_t > 0$), the variance of the $\hat{\omega}_{t+1}$ will be positive. However, this does not neccesarily imply that the supply will be less at $t+1$, since there is a chance that the "news shock" will not be realized. In that case, agents will update their beliefs about the future (scale by $\lambda < 1$), and become less concerned.

2.4 Equilibrium, Market Clearing and Aggregation

2.4.1 Sticky-price Equilibrium

We assume a symmetric monopolistic competition equilibrium in which all intermediate good producing firms have identical behavior. In this equilibrium, at a given time some of the intermediate good producing firms cannot adjust their prices. However, those firms that optimize their profits, decide to charge the same price $\tilde{P}_t$. Therefore, the aggregate price index will be:

$$P_t = [(1-\theta)\tilde{P_t}^{1-\varepsilon} + \theta P_{t-1}^{1-\varepsilon}]^{\frac{1}{1-\varepsilon}} \tag{2.17}$$

If we denote $\tilde{p}_t = \frac{\tilde{P}_t}{P_t}$, then

$$\tilde{p}_t = \left[\frac{1-\theta\bar{\pi}_t^{\varepsilon-1}}{1-\theta}\right]^{\frac{1}{1-\varepsilon}} \tag{2.18}$$

2.4.2 Aggregation

Aggregate price dispersion has a distortionary effect on the aggregate output. If we denote aggregate price dispersion by $\Delta_t = \int_0^1 (\frac{P_t(i)}{P_t})^{-\varepsilon} di$, aggregate output will be the following:

$$Q_t = \frac{A_t {K_t}^{\alpha_k} L_t^{\alpha_l} O_t^{\alpha_o}}{\Delta_t} \tag{2.19}$$

where

$$L_t = \int_0^1 L_t(i)\ di \tag{2.20}$$

$$K_t = \int_0^1 K_t(i)\ di \tag{2.21}$$

$$O_t = \int_0^1 O_t(i)\ di \tag{2.22}$$

In the production factors market, monopolistic distortion caused by the intermediate good producing firms implies that labor, capital and oil are paid below their marginal product.

$$w_t L_t = \alpha_l mc_t Q_t \Delta_t \tag{2.23}$$

$$r_t^k K_t = \alpha_k mc_t Q_t \Delta_t \tag{2.24}$$

$$p_t^o O_t = \alpha_o mc_t Q_t \Delta_t \tag{2.25}$$

where real marginal cost $mc_t = \frac{p_t^{o\,\alpha_o} w_t^{\alpha_l} r_t^{k\,\alpha_k}}{A_t \alpha_o^{\alpha_o} \alpha_l^{\alpha_l} \alpha_k^{\alpha_k}}$ is common for all firms. Under flexible prices, monopoly distortion measured by mc_t is constant and less than unity. However, when prices are sticky, it responds to the real and nominal shocks in the economy. Therefore, an oil price shock affects the inputs market through the perturbation in mc_t.

Optimal price-setting decision ($\tilde{P}_t$) by an intermediate good producing firm is governed by the following equations:

$$\frac{\tilde{P}_t}{P_t} \equiv \tilde{p}_t = \frac{E_t \Sigma_{k=0}^{\infty} (\beta\theta)^k \frac{Q_{t+k}}{C_{t+k}} X_{t,k}^{-\varepsilon} \frac{\varepsilon}{\varepsilon-1} mc_{t+k}}{E_t \Sigma_{k=0}^{\infty} (\beta\theta)^k \frac{Q_{t+k}}{C_{t+k}} X_{t,k}^{1-\varepsilon}} \equiv \frac{N_t}{D_t} \tag{2.26}$$

$$N_t = \frac{\varepsilon}{\varepsilon - 1} mc_t \frac{Q_t}{C_t} + \beta\theta E_t \bar{\pi}_{t+1}^{\varepsilon} N_{t+1} \tag{2.27}$$

$$D_t = \frac{Q_t}{C_t} + \beta\theta E_t \bar{\pi}_{t+1}^{\varepsilon} D_{t+1} \tag{2.28}$$

Decision rules for the intermediate firms and the storage operators in the financial markets, which determine the equilibrium level of oil inventories and futures contracts, are characterized by the following equations:

$$E_t\ (p^o_{t+1}) = E_t\ (\frac{F_t}{P_{t+1}}) \tag{2.29}$$

$$E_t\Big[\frac{1}{1+r_t}\frac{F_t}{P_{t+1}}\Big] = p^o_t - g_1(I_{t+1}, \sigma^2_{t+1}) \tag{2.30}$$

2.4.3 Market Clearing

In equilibrium, net supply of riskless bonds should be zero. Besides, since there is no capital accumulation, aggregate demand for capital is equal to the fixed supply.

$$B_t = 0 \tag{2.31}$$

$$K_t = 1 \tag{2.32}$$

In the oil market, oil supply is determined by the stochastic endowment (Ω_t) and the change in the level of inventories (ΔI_{t+1}). Therefore, the aggregate demand for oil, O_t, is equal to $\Omega_t - \Delta I_{t+1}$.

The oil-exporting country spends all the oil revenues on consumption good produced by the final good producers in the oil-importing country. Therefore, in the equilibrium, goods market clearing implies:

$$C^F_t = p^o_t O_t \tag{2.33}$$

$$C^F_t + C_t = Q_t \tag{2.34}$$

2.5 Calibration and Results

We follow the literature to calibrate the parameters for the utility and production functions. We set $\beta = 0.99$ corresponding to %4 annual steady-state real interest rate. Utility is logarithmic and the parameter $\psi = 1$ implying unit Frisch labor elasticity. There is no capital accumulation in the model, so the aggregate level of capital, $\bar{K}$, is set to 1. The labor, capital and oil elasticities of gross output are set to 0.63, 0.32 and 0.05, respectively. The elasticity of substitution among intermediate goods, ε, is set to 7.66 to match a steady-state price mark-up of %15 implying $\mu = 1.15$. Together with the oil elasticity of gross output, $\alpha_o = 0.05$, the price mark-up matches the average oil consumption share of U.S. GDP, which is 0.04. We assume that the intermediate firms can optimize their profits only once a year, so the Calvo price adjustment parameter, θ, is set to 0.75.

For the baseline analysis, we calibrate the monetary policy using the findings Orphanides (2004). Therefore, we set our baseline parameters to $\phi_R = 0.79$, $\phi_\pi = 1.8$ and $\phi_y = 0.27$. We will later simulate the model using alternative policies by changing the coefficients of the interest rate smoothing parameter and the coefficients of the contemporaneous inflation and the log-deviation of the output.

The persistence parameters for the technology (η), oil endowment (ρ) and the variance (λ) shocks are all set to 0.5. The calibration of these parameters do not have any significant qualitative effect on the results, as long as they are set positive numbers less than one.

Following Gorton et al. (2007), we set the marginal convenience yield parameters for the inventory and the variance at -130 and 40, respectively. The steady-state value of oil endowment and the inventory are chosen to be 0.5 and 0.05.

We solve the model by taking second-order Taylor expansion around deterministic steady-state with zero inflation in order to capture the variance effect and calculate impulse response functions for the specific shocks. To be more precise, the solution method follows the algorithm proposed by Benigno et al. (2010), which proposes a second-order approximation method for the solution of the dynamic stochastic models, where exogenous state variables display time-varying risk.

2.6 Alternative Monetary Policies

In this section we study the response of the economy to oil price shocks under different monetary policy specifications thus exploring the possibilities of systematic policy in dampening or amplifying those adverse effects on the macro economy. We run counter-factual policy experiments similar to the literature to study the effects of monetary policy in a model with storage and financial markets. The existence of storage and financial markets can, intuitively, lead to a different policy proposal, or change the ranking of those policies in terms of macroeconomic effects. This is because of the fact that when good prices are sticky, the monetary authority can affect real interest rate by just changing nominal interest rates, and thus encourage or discourage the storage.

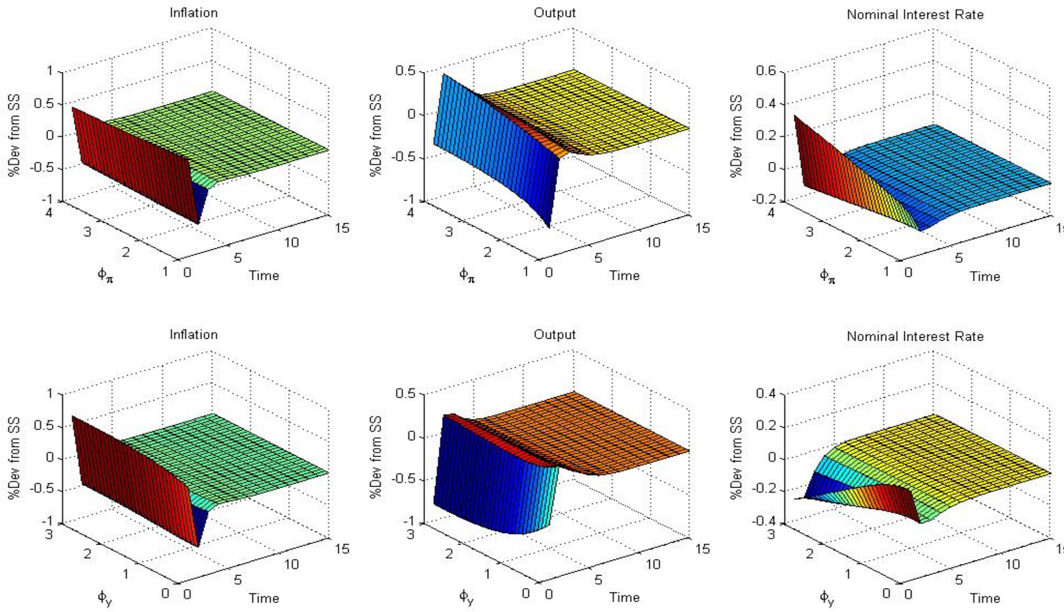

Figure 2.2 : Shock to the variance ($\eta_t = 1$), no realization ($\epsilon_t = 0$ for all t).
The first column depicts each variables response to the shock as a function of the weight on output deviations (ϕ_y) in the interest rate rules, while the second column similarly plots responses as a function of the weight on inflation deviations (ϕ_π).

First, we consider the macroeconomic consequences of different oil price shocks under different Taylor-type interest rate rules. Namely, we fix one coefficient to its benchmark estimate by Orphanides (2001) and change the other one within the reasonable range. First column of Figure 2.2, shows the responses of inflation, output gap and interest rate where ϕ_π is fixed to 1.8, but ϕ_y varies between 0 and 3. Similarly, second column depicts the same dynamics for the fixed $\phi_y = 0.27$, and ϕ_π varying between 1 and 3. The coefficient of inflation should stay above 1 to get (locally) unique equilibrium (Leduc and Sill (2004), Carsltrom and Fuerst (2006)).

Figure 2.2 shows that interest-rate rules that place a high weight on output gap lead to a lower inflation, but not a smaller output loss. Similarly, the rules with high weight on inflation favor output, but also lead to a higher inflation rate.

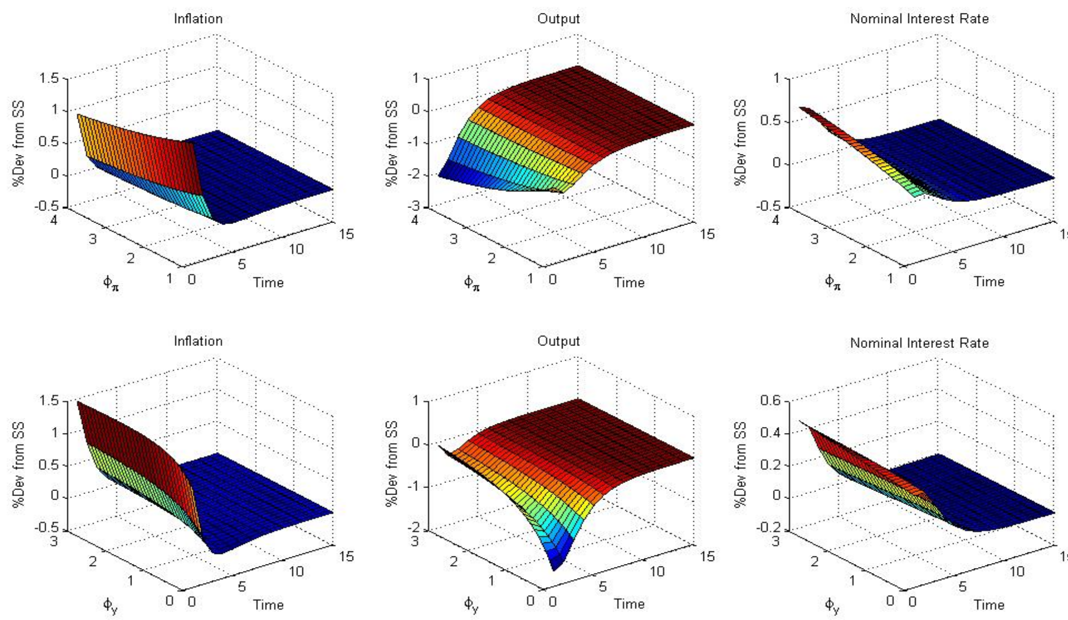

Figure 2.3 : Shock to the mean only ($\varepsilon_t = -1$).
The first column depicts each variables response to the shock as a function of the weight on output deviations (ϕ_y) in the interest rate rules, while the second column similarly plots responses as a function of the weight on inflation deviations (ϕ_π).

For a better understanding of the role of storage and financial markets, we simulate the responses of output gap and inflation to an exogenous supply shock (mean effect) under the similar monetary policy variations. This will help us to compare our results with the ones in the literature (Leduc and Sill (2004), Carsltrom and Fuerst (2006)). Using the same parameters for the monetary policy, Leduc and Sill (2004) finds that interest-rate rules that place a high weight on inflation and low weight on output loss lead to a smaller output loss and inflation. Besides, these weights produce low interest rates. Thus, Leduc and Sill (2004) concluded that low interest-rate rules dampen the recessionary consequences of an exogenous oil supply shock. However, our model does not come up with a clear-cut ranking of the Taylor-type rules in terms of inflation and output gap dynamics perturbed by a supply shock. In other words, a high weight on output gap lowers the loss in output, but also leads to a higher inflation. Similarly, a higher weight on inflation favors inflation, but exaggerates the output loss. Therefore, we can conclude that monetary policy propositions made with a model that lacks storage and financial markets (which is less realistic) can be misleading.

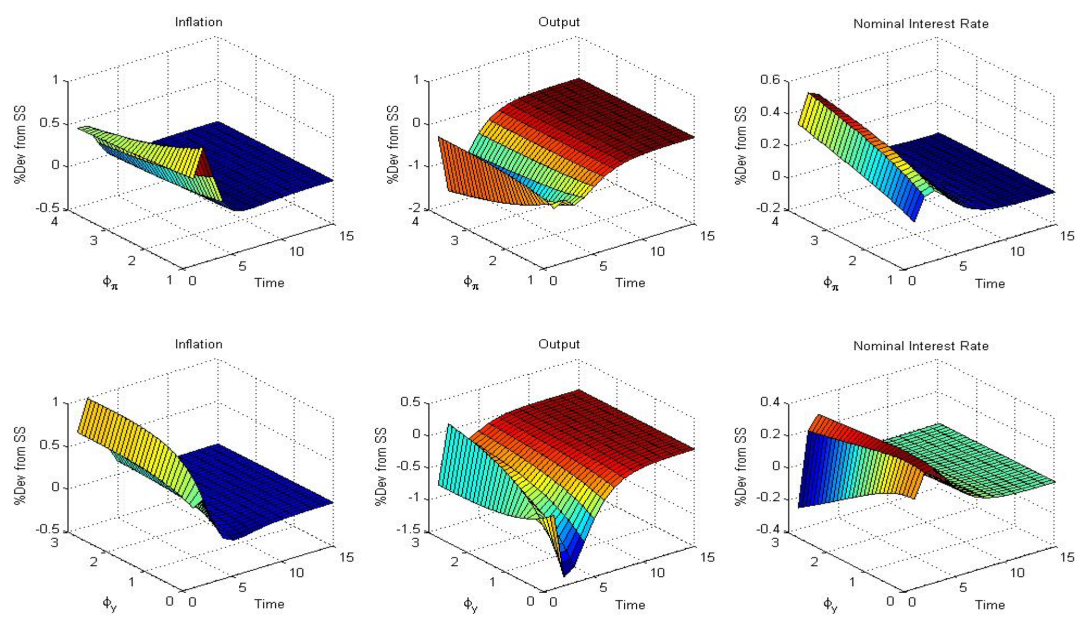

Figure 2.4 : Shock to the variance ($\eta_t = 1$) followed by a shock to the mean ($\varepsilon_{t+1} = -1$).
The first column depicts each variables response to the shock as a function of the weight on output deviations (ϕ_y) in the interest rate rules, while the second column similarly plots responses as a function of the weight on inflation deviations (ϕ_π).

Lastly, we run the same experiment (Figure 2.4) for an "uncertainty shock" followed by a supply shock and simulate the macroeconomic effects. Still the results are ambiguous in terms of better weights. However, this time we can conclude that interest-rate rules that lead to a lower interest rate (high ϕ_y and low ϕ_π) favors inflation rate, and those leading to a higher interest rate (low ϕ_y and high ϕ_π) dampens the output loss.

Since there is not a clear-cut policy ranking within the family of Taylor-type rules based on inflation and output loss dynamics, I perform a single measure ranking for those rules by calculating conditional welfare associated with each combination of (ϕ_y, ϕ_π). I define the welfare associated with a interest-rate policy conditional on a particular state of the economy in period 0 as following:

$$W_0 = E_0 \Sigma_{t=0}^{\infty} \beta^t U(C_t^a, L_t^a) \tag{2.35}$$

where $\{C_t^a\}_{t=0}^{\infty}$ and $\{L_t^a\}_{t=0}^{\infty}$ are defined as the sequences of consumption and labor attained under the specific alternative monetary policies. Besides, we assume that the economy starts from its steady-state value. Since the non-stochastic steady-state is independent of the monetary policy, by setting all state variables equal to their non-stochastic steady-state values at time zero, we assure that the economy begins from the same initial point under all alternative policies. I evaluate the conditional welfare, W_0, to the second order of accuracy by taking second-order Taylor approximation around non-stochastic steady-state¶:

$$W_0 \simeq \frac{U(C,L)}{1-\beta} + \Sigma_{t=0}^{\infty}\beta^t \left[\hat{c}_t - \frac{1}{2}\sigma_{c_t}^2 - L^{1+\psi}(\hat{l}_t + \frac{1}{2}\psi\sigma_{l_t}^2)\right] \tag{2.36}$$

where $\hat{c}_t, \hat{l}_t, \sigma_{c_t}^2$ and $\sigma_{l_t}^2$ are the log-deviation of consumption and labor from their steady-state values and the variance of those variables, respectively.

Figure 2.5 depicts the conditional welfare as a function of (ϕ_y, ϕ_π). In order to get a better idea about the dynamics of conditional welfare, we also plot the maximum value of conditional welfare for each ϕ_y (ϕ_π) as a function of ϕ_π (ϕ_y). For any given value of ϕ_y, the conditional welfare improves as ϕ_π increases. On the other hand, conditional welfare is the highest value when ϕ_y=0 for any given value of ϕ_π. Based on these results, we also plot the nominal interest rate associated with the (ϕ_π, ϕ_y) bundle yielding the highest welfare. It is clear that a Taylor-type policy rule that responds with a higher initial nominal interest rate leads to a higher level of conditional welfare. Besides, this finding holds not only for the actual oil supply shock, but also for the uncertainty shock with and without the realization. We did not include the plots here for those shocks, since the results are very similar.

¶Benigno and Woodford (2004), Gali and Monacelli (2005) show how to derive loss function (the weighted sum of inflation and output gap) from a second-order approximation of W_0. However, we do not have to derive a loss function for the purpose of the analysis in this paper, as we already have a contingent sequence of $\{\hat{c}_t\}$ and $\{\hat{l}_t\}$ obtained by second-degree approximation to the solution of the model under a given monetary policy.

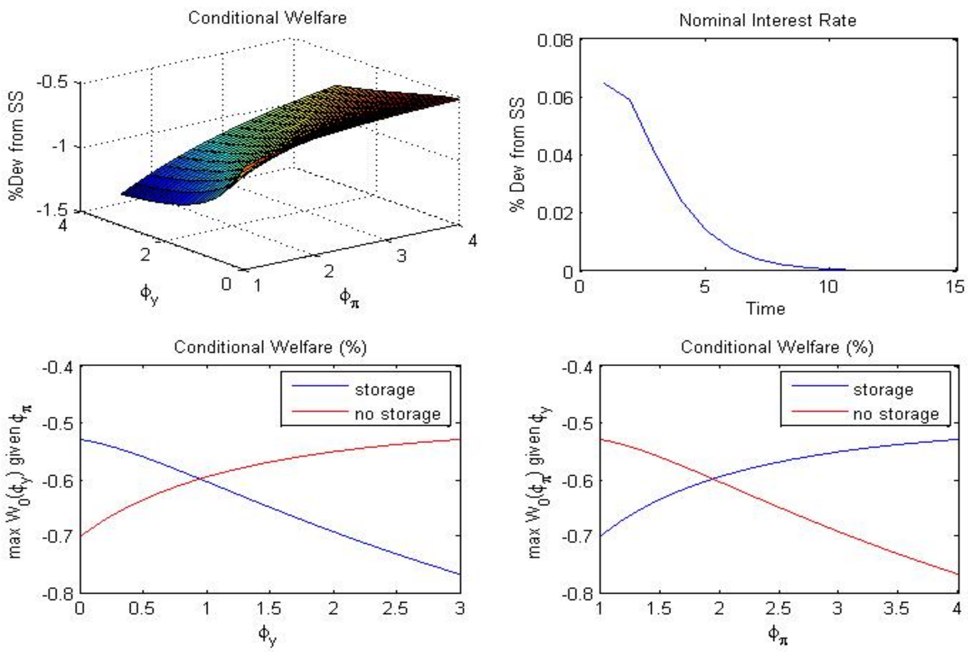

Figure 2.5 : Conditional Welfare and Nominal Interest Rate - Supply Shock.
The graphs depict the conditional welfare as a function of ϕ_π and ϕ_y and the nominal interest rate associated with the (ϕ_π, ϕ_y) yielding the highest welfare.

2.7 Optimal Monetary Policy

To compute the optimal monetary policy, I solve the Ramsey problem. Following the literature (Khan et al. (2003)), I define the optimal monetary policy as a sequence of nominal interest rate, $\{R_t\}_{t=1}^{\infty}$, that maximizes agents' welfare subject to the first-order conditions for the households, the firms, the storage operators and the resource constraint given the exogenous processes for stochastic state variables. The monetary authority maximizes the following Langragian with respect to the Langrange multipliers, $\Lambda_t = \{\gamma_t, \phi_t, \varphi_t, \lambda_t, \zeta_t\}$, and the choice variables, $\Upsilon_t = \{R_t, C_t, L_t, mc_t, p_t^o, N_t, D_t, I_{t+1}, \bar{\pi}_t\}$:

$$
\begin{aligned}
\max_{\Lambda_t,\Upsilon_t} E_0 \Bigg\{ \Sigma_{t=0}^{\infty}\beta^t \Bigg[& log(C_t) - \frac{L_t^{1+\psi}}{1+\psi} + \gamma_t(\frac{1}{C_t} - \beta\frac{R_t}{\bar{\pi}_{t+1}C_{t+1}}) \\
& + \phi_t(N_t - \frac{\varepsilon}{\varepsilon-1}\frac{mc_t}{1-\alpha_o mc_t} - \beta\theta\bar{\pi}_{t+1}^{\varepsilon}N_{t+1}) \\
& + \varphi_t(D_t - \frac{1}{1-\alpha_o mc_t} - \beta\theta\bar{\pi}_{t+1}^{\varepsilon-1}D_{t+1}) \\
& + \lambda_t(N_t - D_t[\frac{1-\theta\bar{\pi}_t^{\varepsilon-1}}{1-\theta}]^{\frac{1}{1-\varepsilon}}) \\
& + \zeta_t(g_1(I_{t+1},\sigma_{t+1}^2) - p_t^o + \frac{\bar{\pi}_{t+1}}{R_t}p_{t+1}^o) \Bigg] \Bigg\}
\end{aligned}
\tag{2.37}
$$

We assume that the government is able to commit to a policy plan set at time zero. To obtain a time invariant commitment policy, we set initial values of predetermined Langrange multipliers equal to their respective non-stochastic steady-state values:

$$\phi_{-1} = \phi \tag{2.38}$$

$$\varphi_{-1} = \varphi \tag{2.39}$$

$$\gamma_{-1} = \gamma \tag{2.40}$$

$$\zeta_{-1} = \zeta \tag{2.41}$$

Again, using the solution method proposed by Benigno et al. (2010), we find that monetary authority overshoots nominal interest rate, output loss and the real oil price. These are the similar dynamics that the economy performs under the benchmark Taylor rule calibrated to the US historical monetary policy. As we can see in Figure 2.6, in the case of increased uncertainty about future oil supply such as “news” shock, storage operators create scarcity in the market by hoarding oil inventories resulting

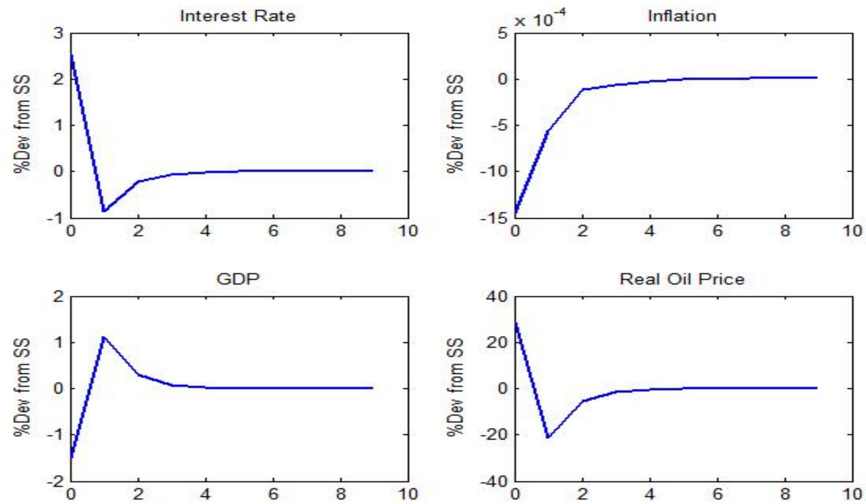

Figure 2.6 : Optimal Monetary Policy - Shock to the variance only ($\eta_t = 1$)

in the real price of oil to spike. Since oil is used in the production, higher input prices lowers demand for oil. On the other hand, labor demand goes down being affected by higher real marginal cost in intermediate goods production. The latter effect would not occur if the prices were flexible. However, under sticky prices the factor market is distorted by the fluctuations in the real marginal cost. All these effects combined cause a 1.5% output loss during the first period.

However, unlike what we observed under the benchmark Taylor rule, inflation is almost at zero level when the monetary authority employs the optimal policy. Although the optimal monetary policy stabilizes the inflation by increasing nominal interest rate more than the benchmark rule, it cannot avoid the 1.5% output loss. During the next period, if supply disruption does not occur as in stochastic oil endowment remaining at the steady-state level, storage operators update their beliefs about the future and become less concerned. Therefore they decrease the level of oil inventory increasing the abundance of oil in the economy. The real oil price goes below its steady-state level and, demand for labor increases, thus output climbs above its steady-state level.

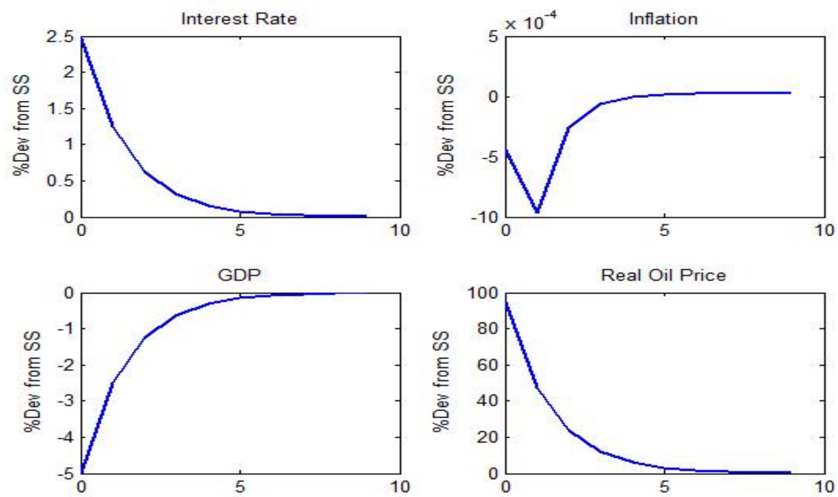

Figure 2.7 : Optimal Monetary Policy - Shock to the mean only ($\epsilon_t = -1$)

The effects of actual supply shock (mean shock) on a macro economy under the optimal monetary policy differs from the effects of uncertainty shock both in terms of the dynamics and magnitude. Figure 2.7 shows that in the aftermath of a supply shock, monetary policy sets nominal interest rate 2.5% above its steady-state value to pacify the large and persistent macro effects. Actual supply shock creates a persistent oil scarcity in the economy. Although inflation is again stabilized by the monetary authority, output goes down by 5%. The existence of storage and financial markets is an obstacle for the monetary authority to control the output by lowering the nominal interest rate. In fact, lower interest rate will decrease the cost of storage and thus encourage the storage operators to increase the level of inventory. This shrinks the quantity of oil available in the spot market, already dampened by the actual supply shortfall. More scarcity of oil induces higher real oil prices, less demand for oil and labor (through marginal cost) and consequently a deeper recession.

2.8 Conclusion

This study examines the role of monetary policy in dampening or amplifying the adverse effects of oil price surges. There is a general consensus in the literature that tight monetary policy associated with the oil price spikes of 1970-2000 exaggerated inflation and output loss as a result of these spikes. In contrast with the literature, which ignores storage and financial markets, we find that neither the interest-rate peg abolishes the adverse effects nor low-interest rate rules clearly lead to a higher welfare compared to higher interest-rate rules. Instead, optimal monetary policy dictates higher nominal interest rates as a response to an oil price shock, regardless of the source, which smooths inflation but could lead to a 1-2% output loss. The source of the shock plays an important role in determining the magnitude and variation of the nominal interest rate. As a future work, it would be interesting to separate the effect of strategic investments from those incurred by precautionary demand motives, as a significant part of inventories are supposedly not commercially driven. Besides, an open economy extension of this model with three countries, international borrowing and free exchange rates can shed a light on the relationship between US exchange rates and the price of oil.

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